The influence of sensor placement on in-situ ultrasound wave velocity measurement

Francisco Arriaga
Department of Forest and Environmental Engineering and Management. Universidad Politécnica de Madrid, Madrid, Spain, francisco.arriaga@upm.es

Daniel F. Llana
Department of Forest and Environmental Engineering and Management. Universidad Politécnica de Madrid, Madrid, Spain, danielfllana@gmail.com

Roberto Martínez
Department of Agroforestry Engineering. Universidad Santiago de Compostela, Lugo, Spain, robertodmartinezlopez@gmail.com

Miguel Esteban
Department of Forest and Environmental Engineering and Management. Universidad Politécnica de Madrid, Madrid, Spain, miguel.esteban@upm.es

Guillermo Íñiguez-González
Department of Forest and Environmental Engineering and Management. Universidad Politécnica de Madrid, Madrid, Spain, guillermo.iniguez@upm.es

Abstract

Ultrasound wave velocity was measured in 30 pieces of Spanish Scots pine (*Pinus sylvestris* L.), 90 x 140 mm in cross-section and 4 m long. Five different sensor placement arrangements were used: end to end (V_0), face to opposite face, edge to opposite edge, face to same face and edge to same edge. The pieces were successively shortened to 3, 2 and 1 m, in order to obtain these velocities and their ratios to reference value V_0 for different lengths and angles with respect to the piece axis for the crossed measurements. The velocity obtained in crossed measurements is lower than V_0. A correction coefficient for crossed velocities is proposed, depending on the angle, to adjust them to the V_0 benchmark. The velocities measured on a surface, are also lower than V_0, and their ratio with respect to V_0 is close to 0.97 for distances equal to or greater than 18 times the depth of the beam.

Keywords: nondestructive techniques, sensors positioning, ultrasonic wave, wave velocity

Introduction

Non-destructive methods are used in the evaluation of existing timber structures, among other uses. For example, determination of wave transmission velocity makes it possible to estimate the mechanical properties of structural elements. Studies and laboratory research in this field are usually performed by measuring the Time-of-Flight (ToF) of the wave between the ends of the pieces.

This is the best way to measure ToF, in a direction parallel to the axis of the piece and approximately parallel to the grain. But in practice, during the in situ inspection of timber structures this is not possible, and it is necessary to place sensors differently. It is usually impossible to access the ends of timber pieces in existing structures, and ToF has to be measured to determine wave velocity by placing one of the sensors on one face, and the other in the opposite face, in a segment with a length less than the total length of the piece. We term this arrangement ‘crossed measurement’. There is therefore a small angle between the straight line joining both sensors and the grain. This angle is usually from 1.5 to 10º, and this deviation give rise to a slightly lower velocity compared with measurement parallel to the grain.

In cases such as timber floor joists where only the lower edges are visible, or in columns which are embedded in walls and covered with 1 or 2 cm of plaster, ToF measurements must be done by placing both sensors on the same face of the timber piece. We term this arrangement ‘surface measurement’. The velocity obtained using this procedure usually gives slightly lower values than measurement parallel to the grain.

By these methods (crossed and surface measurements) ToF are measured in partial segments of the length of the piece, so the information collected by the wave is less representative of the overall quality of the piece. The correlation between mechanical properties and wave velocity varies depending on the segment length considered.

The objective of this research is to analyze the effect of these different sensor positions on ultrasound wave velocity measurement in existing timber structures (crossed and surface measurements) with respect to end-to-end measurement, together with the influence of the length of the tested central segment of the piece.

Material and methods

This study used 30 pieces of dry planed structural Spanish Scots pine (*Pinus sylvestris* L.) with nominal dimensions of 90 by 140 by 4000 mm. The moisture content (MC) of these timber specimens was measured using an electrical resistance moisture meter (Gann RTU600, Gann Mess-u, Regeltechnik Gmbh, Germany) according to the EN 13183-2 (2002) standard. The average MC of the pieces was 9.1%, with a coefficient of variation (COV) of 10.7%. The maximum and minimum values were 8 and 11.1%, respectively. No correction for MC was made for modulus of elasticity or for velocity, due to the low variation of MC in the timber pieces.

Time of flight measurements

Ultrasound wave Time-of-Flight (ToF) was measured using the Sylvatest Duo (CBS-CBT, France) with conical sensors at 22 kHz. This device determines an average ToF obtained from 5 consecutive readings for each measurement. Measurements were performed using five different sensor placement arrangements: longitudinal (parallel to the grain) by placing sensors at the ends of each specimen, one on each end (V_0); crossed, by placing one sensor on a face and the other on the opposite face (V_{cf}); crossed by placing one sensor on an edge and the other on the opposite edge (V_{ce}); and finally, surface measurement by placing both sensors on the same face (V_{sf}) or on the same edge (V_{se}), figure 1.

Wave velocity (V) was determined according to the following equation 1, where L is the distance between sensors (m) and T is the average time-of-flight measured.

$$V = L/T \tag{1}$$

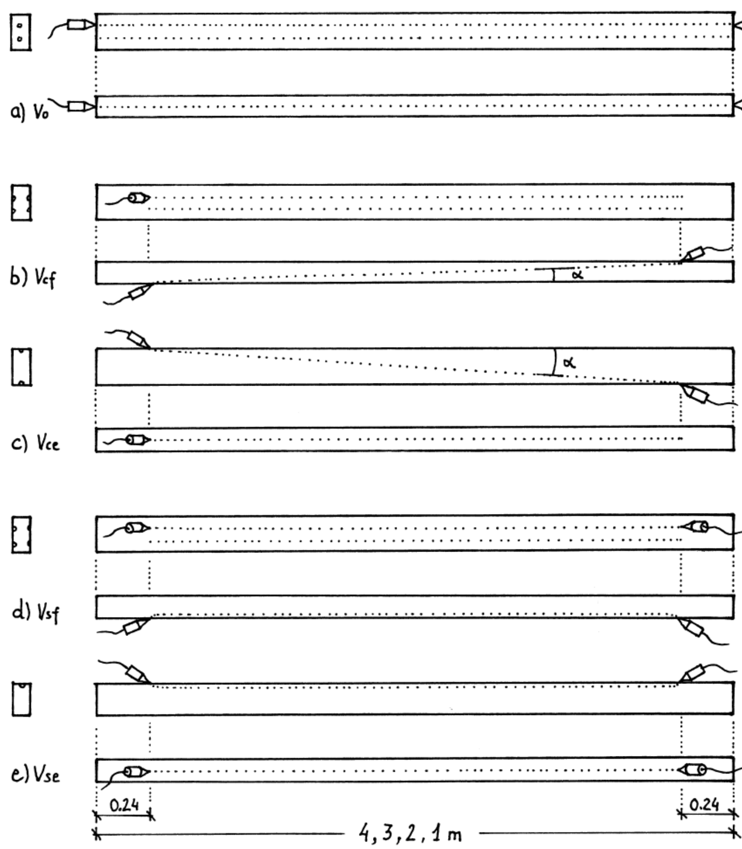

Figure 1— Sensor placement arrangements: a) Parallel to the grain; b) Crossed measurement between opposite faces; c) Crossed measurement between opposite edges; d) Surface measurement on the same face, and e) Surface measurement on the same edge.

Crossed and surface measurements were performed at a distance equal to 240 mm from the end of the piece in order to avoid any possible border effect. For each arrangement, two measurement points were considered, located at one and two thirds of the depth of the piece, except in edge measurement where due to its narrowness only one measurement was made, figure 2. Sensor orientation in crossed and surface measurements was at an angle equal to or slightly less than 45º with respect to the timber surface. The depth of the sensor point in the timber was 10 to 12 mm when parallel to the grain and inclined.

Following initial measurements on the 4-m-long wood specimens, each piece of wood was subsequently reduced to 3 m long by cutting a 0.5 m long section from each end. This procedure was repeated two more times to obtain wood specimens of 3, 2 and 1 m in length. Figure 3 shows the cutting procedures to obtain the target lengths. In this way, parallel to the grain ToF and velocity V_0 was obtained for pieces 4, 3, 2 and 1 m long, together with crossed measurements for 3.52, 2.52, 1.52 and 0.52 m lengths, corresponding to nominal distances between sensors and angles of 3.521 m/1.465º, 2.522 m/2.045º, 1.523 m/3.388º and 0.528 m/9.819º for V_{cf}, and 3.523 m/2.277º, 2.524 m/3.180º, 1.526 m/5.262º and 0.538 m/15.068º for V_{ce}. To summarize, velocities in crossed arrangements were obtained for 8 different angles from 1.627º to 15.068º and their ratios with respect to the benchmark value V_0 at the closest corresponding distance (4, 3, 2 and 1 m) were calculated.

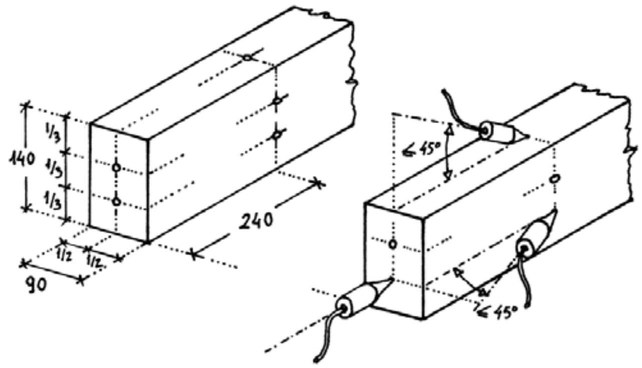

Figure 2— Sensor positioning.

In a similar way, ToF and velocity in surface measurement was obtained for each length (3.52, 2.52, 1.52 and 0.52 m) on the faces V_{sf} and the edges V_{se}, calculating the ratios with respect to the parallel velocity V_0.

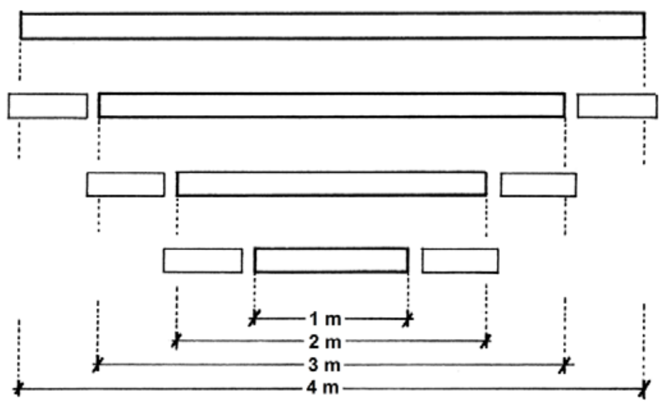

Figure 3— Procedure for reducing the length of the specimens.

Static modulus of elasticity

The static modulus of elasticity (*MOE*) of timber pieces were determined by static bending test according to European Standard EN 408 (2010+A1:2012). The test piece is simply supported and symmetrically loaded in bending at the thirds of a span equal to 18 times the depth of the piece, Figure 4. This test was performed when the timber pieces were 3 m long.

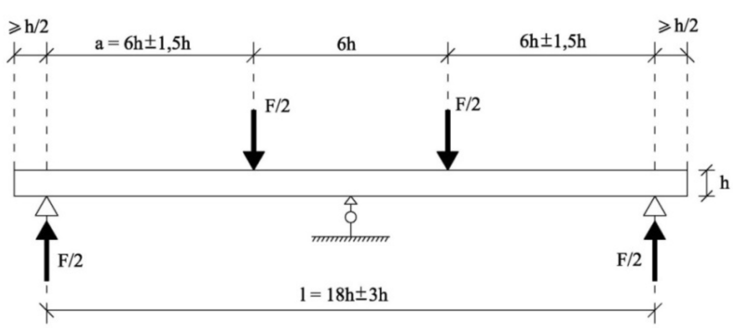

Figure 4— Arrangement for bending test according to European Standard EN 408 (2010+A1:2012).

One of the most relevant singularities of the timber grading process is knottiness, which can be characterized using a simplified parameter known as CKDR (Divos 2002). The knot diameter ratio (KDR) is knot diameter divided by the depth or width of the piece. The Concentrated KDR (CKDR) is the sum of the KDRs of the knots existing in any 15 cm length of a timber piece. The maximum CKDR which includes all 4 faces represents the quality of the piece, Figure 5. This value of CKDR is obtained for the worst cross section in the whole length of the piece, and it varies from 0 to 1. The CKDR was calculated for each length of the specimen (4, 3, 2 and 1 m) obtaining average values of 0.13, 0.13, 0.12 and 0.10, respectively. This means that knottiness is practically constant in all lengths.

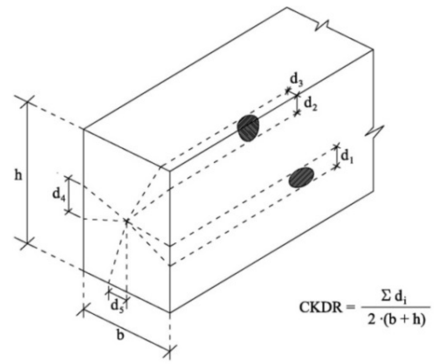

Figure 5— Knot Diameter Ratio (CKDR).

Results and discussion

Angle effect

Figure 6 shows the linear regression between the V_α/V_0 ratio and cos (α), where α is the angle formed by the line between sensors, in crossed measurements, and the direction of the axis of the piece. The coefficient of determination is R^2 = 0.80 and the equation is,

$$V_\alpha / V_0 = 5.2563 \ \cos\alpha - 4.28319 \qquad (2)$$

If angle α=0 the ratio V_α/V_0= 0.973 which is approximately equal to the ratio between surface measurements and end to end measurements, as it will be shown later. This value, slightly different to 1, could be explained by an effect originated by the position of sensors in faces (or edges) and not in the ends of the piece.

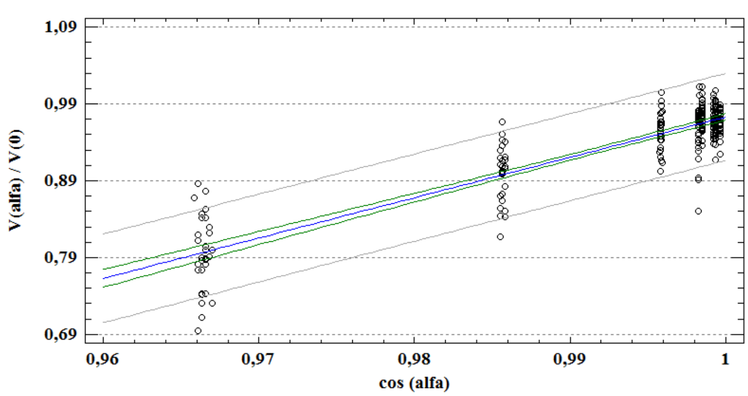

Figure 6— Linear regression: $V\alpha/V_0$ ratio vs. cos (α).

The influence of the angle of the grain can be estimated by means of the Hankinson formula (Hankinson 1921). If the property is known for the direction parallel and perpendicular to the grain (P_0 and P_{90}, respectively) the property for an inclined direction, P_α may be obtained according to the following equation,

$$P_\alpha = \frac{P_0}{\frac{P_0}{P_{90}} \sin^2 \alpha + \cos^2 \alpha} \tag{3}$$

and dividing both members of the equation by P_0 and denominating the P_0/P_{90} ratio k, equation 3 takes the following form,

$$\frac{P_\alpha}{P_0} = \frac{1}{k \sin^2 \alpha + \cos^2 \alpha} \tag{4}$$

According to some authors the ratio (k value) velocity at 0º over velocity at 90º to the grain is in the order of 2.7 (Gerhards 1982). A ratio of k=3 was obtained for ultrasound velocity in Scots pine in previous studies (Íñiguez et al. 2009). Better agreement with the experimental results obtained in this work for angles between 1.4 and 15º was deduced for k = 5.5. Figure 7a shows equation 4 for a k value of 5.5. Figure 7b compares the results obtained by equations 2 and 4 in the interval 1 to 15º. Although the curves are very close to each other, equation 2 presents a better fit with experimental results. The V_α/V_0 ratio will be termed the modification factor for angle k_α, and it will be used to correct the velocity obtained in crossed measurements.

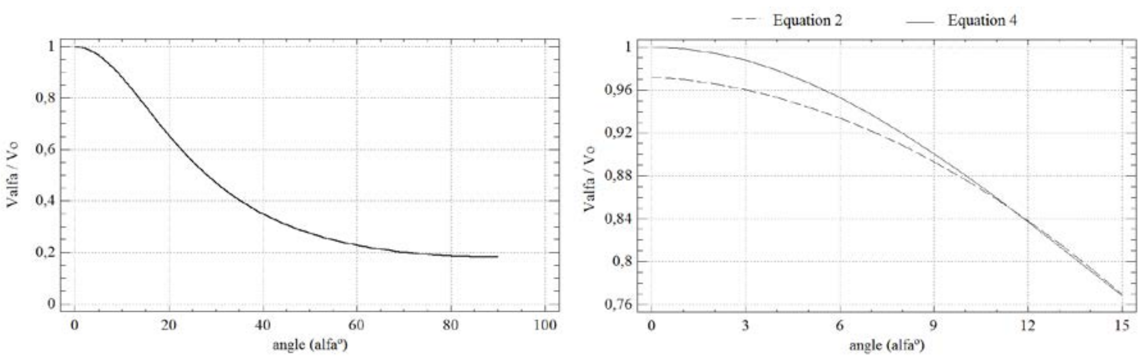

Figure 7— a) Hankinson – eq. 4; b) Equation 2.

Velocity decreases as grain angle increases, although there is no linear relationship. However, it is close to being a linear relationship at certain angles. Some authors estimate that there is 1% velocity loss per degree increase in grain angle up to about 30º (Gerhards 1982). In a previous work (Íñiguez 2007) the velocity parallel to the grain was measured end to end in 80 150x200 mm cross-section 4 m long pieces of radiata pine, obtaining a mean value of V_0 = 4859 m/s. The velocity from face to opposite face over a length equal to 18 times piece thickness was also measured with a mean value of V_{cf} = 4744 m/s. The angle between sensors and the axis of the piece was α = 2.38º. This fall in velocity is equivalent to a 1% fall in velocity for each 1º of angle to the grain.

Surface measurements

Table 1 shows the average ratios between the velocities obtained in surface measurements (sensors on the same face or the same edge) and the velocities measured parallel to the axis of the piece (sensors at the ends of the piece). Figure 8 includes the analysis of variance of these ratios and for each length interval. It can be seen that the “surface” velocity is slightly lower than the “parallel” velocity, except for interval distances of 1-0.52 m in edge measurements. Furthermore, the ratio seems to be close to 0.97 for distances equal to or bigger than 2.52 m. This ratio will be termed the correction factor for surface measurement (k_{sf} and k_{se} for face and edge measurements, respectively).

Table 1— Average values of ratios between velocity measured in the same face or edge (V_{sf} or V_{se}) and velocity measured from end to end (V_0) for each length.

Length (m)	4-3.52	3-2.52	2-1.52	1-0.52
$k_{sf} = V_{sf}/V_0$	0.964	0.967	0.945	0.978
$k_{se} = V_{se}/V_0$	0.971	0.983	0.985	1.041

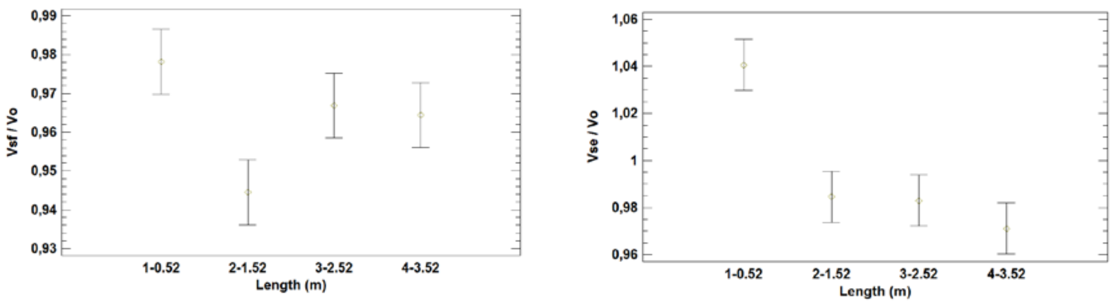

Figure 8— Means plot of one-way analysis of variance for each length. Left: the ratio between velocity measured in the same face (V_{sf}) and end to end velocity (V_0). Right: ratio between velocities measured in the same edge (V_{se}) and end to end velocity (V_0).

A similar value of the correction factor k_{sf} was obtained in previous studies (Íñiguez 2007, Arriaga et al. 2009). The velocity parallel to the grain (V_0) and the velocity from face to opposite face over a length equal to 18 times piece depth (V_{sf}), were measured in 80 150x200 mm cross-section 4 m long pieces of radiata pine. The ratio V_{sf}/V_0 obtained was 0.972, which is very close to the values of table 1.

MOE prediction

The mean MOE obtained was 11776 N/mm^2 with a coefficient of variation, CoV = 12% and the mean velocity from end to end of 3 m long timber pieces was V_0 = 5340 m/s with a CoV = 6%. Figure 9 shows the frequency histogram for both parameters.

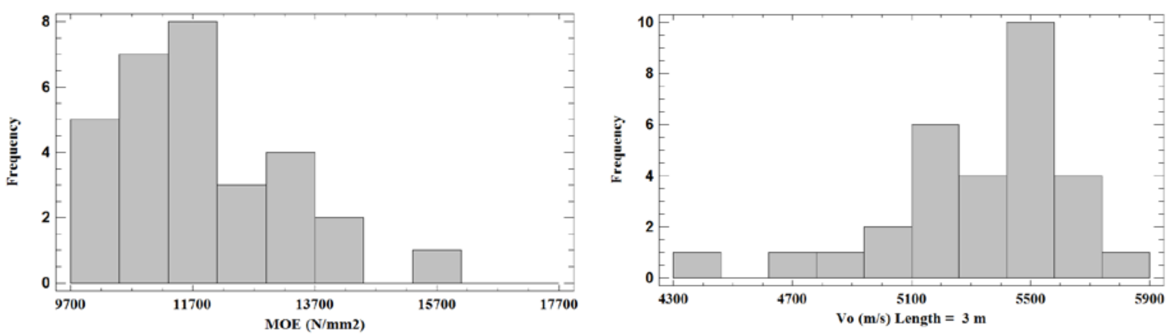

Figure 9— Frequency histogram. Left: MOE, and Right: velocity measured from end to end in 3 m long pieces.

The main purpose of determining wave transmission velocity is to correlate it with the MOE of timber pieces. In this work, the velocity was obtained for 4 different lengths (4, 3, 2 and 1 m) so that MOE can be predicted for each segment of length. Table 2 summarizes the linear regressions between MOE and velocity $V=V_0$ for each length segment, according to the equation,

$$MOE = A \cdot V + B \qquad (5)$$

The coefficient of determination does not vary very much for different lengths (0.42 to 0.49), and the highest correlation corresponds to lengths 2 to 3 m long. This means that the best prediction of MOE would be obtained for a central segment of beams 2 to 3 m long (14 to 21 times the depth, h, of the beam).

In practice, in-situ ToF measurements have to be performed between opposite faces or edges, or even between two points of the same face or edge. In a similar way to the correlation established between MOE and V_0 in table 2, linear regressions can be established between MOE and “crossed” or “surface” velocities for 4 different lengths (3.52, 2.52, 1.52 and 0.52 m).

Table 2— Linear regression equation parameters for MOE vs. $V=V_0$ (equation 5).

L (m)	A	B	R^2
1	-4190	2.867	0.44
2	-6322	3.330	0.49
3	-4125	2.978	0.46
4	-3187	2.836	0.42

Table 3 summarizes the linear regressions between MOE and velocity $V=V_{cf}$ and $V=V_{ce}$ for each length segment, according to equation 5. Crossed velocity values have been corrected for angle using the k_α coefficient (equation 2). These results show that the correlation drops to unacceptable values for a measurement distance of 0.52 m (approximately 4 times the depth of the beam, h), while the best results are obtained for pieces 2.52 m long (18h). Using the mean value of both measurements does not give rise to a notable improvement in this prediction.

Table 3— Linear regression equation parameters for MOE vs. $V=V_{cf}$ and V_{ce} (equation 5).

	MOE vs V_{cf}/k_α			MOE vs V_{ce}/k_α			MOE vs $V_{c,mean}$		
L (m)	A	B	R^2	A	B	R^2	A	B	R^2
0.52	1458	1.848	0.18	5752	1.086	0.06	729	1.985	0.15
1.52	-1507	2.464	0.30	-6271	3.311	0.53	-5905	3.261	0.46
2.52	-2250	2.624	0.45	-4600	3.037	0.50	-3890	2.918	0.49
3.52	-2338	2.692	0.41	-735	2.376	0.35	-1746	2.573	0.38

$V_{c,mean}$ mean value of V_{cf}/k_α and V_{ce}/k_α

Table 4 summarizes the linear regressions between MOE and velocity $V=V_{sf}$ and $V=V_{se}$ for each length segment, according to equation 5. The values of surface velocities have been corrected using the k_{sf} or k_{se} coefficient (table 1). Although these results are similar to those of the crossed measurements, they show slightly lower coefficients of determination.

Table 4— Linear regression equation parameters for MOE vs. $V=V_{sf}$ and V_{se} (equation 5).

	MOE vs V_{sf}/k_{sf}			MOE vs V_{se}/k_{se}			MOE vs $V_{s,mean}$		
L (m)	A	B	R^2	A	B	R^2	A	B	R^2
0.52	1949	1.765	0.27	2538	1.661	0.22	-169	2.147	0.31
1.52	-788	2.313	0.33	3004	1.615	0.21	-506	2.261	0.31
2.52	-3353	2.833	0.46	-1791	2.542	0.39	-3570	2.875	0.45
3.52	-2721	2.747	0.43	-2016	2.614	0.42	-2696	2.743	0.43

$V_{s,mean}$ mean value of V_{sf}/k_{sf} and V_{se}/k_{se}

Conclusions

A correction coefficient of ultrasound wave velocity is proposed, to adjust ToF measurements in crossed faces or edges, depending on the cosine of the angle between the line connecting the sensors and the direction of the grain for angles of from 1.4 to 15º. The value is corrected to the reference velocity parallel to the grain. Hankinson's formula can be used for this correction, although it deviates from experimental mean values by around 2%, from 1.4 to 15 °.

A ratio equal to 0.97 was deduced between ultrasonic wave velocity obtained by means of surface measurement with respect to measurement the parallel to the grain, for distances equal to or greater than 2.52 m (18 times the depth of the beam, h). Under this distance surface measurement is not recommended.

The best prediction of MOE was obtained for a central segment of the beam of 2 to 3 m (14h to 21h) when velocity is determined by end to end measurement. The correlation between MOE and crossed and surface velocity is slightly lower than it is parallel to the grain. The best results obtained by crossed and surface velocity were for a central segment 2.52 m length (18h).

These results correspond to a small number of specimens, and therefore findings should be interpreted as preliminary. The authors will extend this research to cover more conifer species and other ToF measurement devices.

Acknowledgments

Ministerio de Economía y Competitividad. Plan Nacional I+D+i 2008-2011. Proy.: BIA 2010-18858. We would like to thank Ramón García Lombardero for his helpful work in the INIA lab, Spain.

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United States Department of Agriculture

Proceedings

19th International Nondestructive Testing and Evaluation of Wood Symposium

Rio de Janeiro, Brazil
2015

Forest Service, Forest Products Laboratory
University of Campinas, College of Agricultural Engineering
Brazilian Society of Non-Destructive Testing and Inspection

General Technical Report
FPL–GTR–239

September
2015

Abstract

The 19th International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the University of Campinas, College of Agricultural Engineering (FEAGRI/UNICAMP), and the Brazilian Association of Nondestructive Testing and Evaluation (ABENDI) in Rio de Janeiro, Brazil, on September 22–25, 2015. This Symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many NDT/NDE users, suppliers, international researchers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, lumber, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world. The technical content of the 19th Symposium is captured in these proceedings.

Keywords: International Nondestructive Testing and Evaluation of Wood Symposium, nondestructive testing, nondestructive evaluation, wood, wood products

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September 2015

Ross, Robert J.; Gonçalves, Raquel; Wang, Xiping, eds. 2015. Proceedings: 19th International Nondestructive Testing and Evaluation of Wood Symposium. General Technical Report FPL-GTR-239. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 688 p.

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